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Exergy accounting of energy and materials flows in steel production systems

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Abstract

A life-cycle inventory (LCI) of steel based on exergy values is presented. Exergy accounting of energy and materials flows for distinct steel production processes — conventional integrated, semi-integrated and new integrated with smelt reduction — is used to calculate and compare exergy losses and efficiencies for each case. The exergy LCI provides an integrated measure of resources, products and wastes at different aggregation levels, from single unit operations and upstream production steps to steel plants and production routes. Exergy values for pollution and wastes are presented and discussed. A sensitivity analysis is performed in order to test how variations in some parameters affect the results of the total exergy accounting for the different steel production routes.

1. Introduction

Beyond the domain of engineering, exergy analysis has been applied to strengthen the biophysical foundations of economics. Exergy can be used as a measure of the potential work embodied in energy and material resources, products and wastes. As a common measure for energy carriers and materials, exergy provides aggregated information that might be used in different ways. As a general measure of technical efficiency or as a first-order approximation of the environmental impact of wastes, exergy can account for the generation of irreversibilities through economic activities [1,2].

Exergy analysis has been used to evaluate energy conversion and utilization by (national) economies [3–5] and for particular industrial processes. Most of these studies have shown large opport-

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Nomenclature

B	exergy
BF	blast furnace
BFG	blast furnace gas
BOF	basic oxygen furnace
COG	coke oven gas
DRI	direct reduction iron
EAF	electric arc furnace
IISI	International Iron and Steel Institute
NG	natural gas
OHF	open hearth furnace
Ψ	exergy efficiency

unities for improvements in energy efficiency in industrial processes and have indicated some measures and economic sectors for which priorities should be assigned for efficiency gains. Studies that have dealt specifically with steel production processes have revealed the sources of exergy losses and evaluated distinct technological alternatives to improve energy and exergy efficiencies [6,7].

Looking at exergy flows from single industries to entire economies, as well as from individual processes to a cluster of interlinked industrial systems,[1] constitutes a promising research field that may lead to new insights about patterns of production, social distribution and use of natural resources and of pollution burdens, structural reorganization and trade-offs from technological changes. In particular, exergy life-cycle analysis offers an accounting method that can be used for these integrated approaches.

In this article, we have attempted to apply the exergy accounting method, as adopted in previous studies [8–10], to a life-cycle inventory (LCI) of steel production routes. Exergy inputs/outputs, exergy losses and efficiencies for each production step, including disaggregated exergy values for wastes, are presented and discussed. In the end, a sensitivity analysis is performed in order to test how variations in some parameters affect the results of the total exergy accounting for the different steel production routes.

2. Methodology

The concept of exergy incorporates a measure of the potential work obtainable from a system or flow. Other thermodynamic potentials, such as Gibb's free energy, Helmholtz's free energy, available work and availability, define potential work for specified constraints. We use the function exergy B defined as [1–3,11]

[1] The term 'industry' here refers to a general meaning, which includes agriculture, transport, etc.

$$B = U + P_0 V - T_0 S - \sum \mu_{0i} n_i, \quad (1)$$

with internal energy U, pressure P, temperature T, entropy S, chemical potential and number of moles of each component μ_i and n_i. The subscript ‘0’ denotes the system when it is in equilibrium with its environment. Exergy measures the maximum work that can be obtained from the system in its interaction towards equilibrium with the environment.

The exergy content of a determined system is divided into several components, such as kinetic, electro-magnetic, physical and chemical.[2] Once the environmental reference state is given, the exergy content of any flow of energy and matter can be calculated. Physical exergies take into account temperature and pressure differences from the environment. Chemical exergies include both reaction and concentration components. Szargut et al. [11] have proposed a method and calculated chemical exergies for hundreds of compounds.[3] The chemical exergies of flows involved in steel production were calculated using these exergy tables and composition data (i.e., mass fractions of each compound from which the resources, products and wastes are constituted).

2.1. Exergy balances

Given the physical and chemical exergies B of energy and material carriers for each step of a given production process, we can calculate exergy losses according to the following exergy balance, depicted in Fig. 1,

$$B_{\mathrm{inputs}} = B_{\mathrm{products}} + B_{\mathrm{losses}} + B_{\mathrm{wastes}}. \quad (2)$$

The sum of exergies of the energy and material resources is denoted by B_{inputs}. The main product and byproducts exergies are both included in B_{products}. The exergy embodied in air emissions, water effluents and solid wastes is denoted by B_{wastes}. The term B_{losses} includes irreversibilities

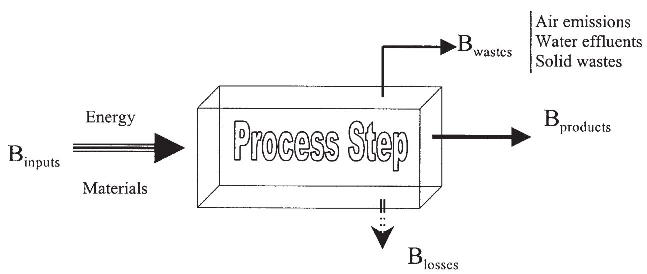

Fig. 1. Exergy accounting for a process step, which can represent any industrial system such as a particular production step, a steel plant or the production route of a reference steel product.

[2] The exergy accounting for steel production processes provided here considers physical and chemical exergies only, due to the negligible influence of kinetic and electro-magnetic exergies in these processes.

[3] The atmosphere, the ocean and the earth’s crust taken separately constitute the environment. Some conceptual and practical issues arise with any environment definition. See Refs. [2,12–14] for a detailed discussion.

and part of the exergy output that is not used.[4] Note that the difference between wastes and byproducts is chosen arbitrarily as this may change over time. For the exergy losses, the exergy balance gives:

$$B_{\text{losses}}=B_{\text{inputs}}-B_{\text{products}}-B_{\text{wastes}}. \tag{3}$$

We can define some proper exergy efficiencies Ψ, which are discussed later, as follows:

$$\Psi_1=(B_{\text{products}}+B_{\text{wastes}})/B_{\text{inputs}}, \tag{4}$$

$$\Psi_2=B_{\text{products}}/B_{\text{inputs}} \tag{5}$$

and

$$\Psi_3=B_{\text{main product}}/B_{\text{inputs}}. \tag{6}$$

The complement of Ψ_1 (i.e., $1-\Psi_1$) indicates the fraction of input exergy that was lost. For instance, if Ψ_1 is equal to 0.65, it means that 35% of the exergy inputs were lost (with the exergy of wastes excluded). The index Ψ_2 indicates the useful exergy (exergy embodied in the main product and in the byproducts) obtained from the exergy inputs. And the index Ψ_3, in turn, is related only to the exergy of the main product. The Ψ_1 efficiency is always higher than the Ψ_2 efficiency, which is equal to, or higher than, the Ψ_3 efficiency. A comparison between Ψ_2 and Ψ_3 provides a fairly good indication about the contribution of one particular production step to the overall production system.

In the case of steel production systems, several byproducts — like BFG or COG — are essential to the internal exergy efficiency of the steelwork plants, whereas other byproducts — like slags, tar or ammonia, among others — can be used in other economic activities. For the perspective assumed in this study, Ψ_2 is the most appropriate efficiency indicator to allow comparisons between different steel production routes, because it considers products and byproducts as useful outputs and deducts the exergy embodied in wastes.

2.2. Steel production systems

We considered three main steelmaking processes: conventional integrated (pelletization, sinter and coke plants–blast furnace–BOF route), semi-integrated (pelletization and DRI plants–EAF route) and new integrated with smelt reduction (pelletization plant–COREX–BOF/EAF route). Liquid carbon steel from oxygen or electric furnaces is chosen as the reference product in order to compare the distinct routes. The contributions from casting, rolling and finishing production steps from materials transportation are not included. A more complete life-cycle inventory for steel should consider other steps, like machine and building manufacturing, production of inputs

[4] There is no standardized nomenclature for this balance yet. Instead of using exergy loss, some authors prefer expressions like exergy destruction or exergy consumption [6,9]. The authors commonly refer to exergy loss as exergy destruction plus wastes.

such as steel and cement used in machine and building manufacturing, as well as inputs used in mining steps, such as explosives.

Tables 1–4 summarize the parameters adopted in a matrix. Rows represent production and columns represent consumption of each production step. Therefore, each cell a_{ij} represents the quantity of product i (shown as rows) utilized to produce one unit of the main product of j step (shown as columns). For instance, a_{ij} can represent the input mass of coke [0.358 metric tonnes (t)] to produce 1 t of pig iron in the blast furnace, or represent the input electricity (0.5 kWh) to produce 1 N m^3 of oxygen gas (see Table 1). Byproducts and some other products, like ferroalloys, dolomite, nitrogen, refractories, compressed air, steam, fuel gases, recycled materials, graphite electrodes and water, are included in the exergy accounting by production step in order to calculate exergy losses and efficiencies.

Instead of focusing on one particular industrial system (e.g., a specific plant or country), we have used values for inputs and pollutants based on an extensive international database using various sources [15–20]. Figures do not represent typical or average practices due to the wide range of plant data; they can only be considered as indicative. These values are used in a model [21] that incorporates other mass and energy flows from the main steel production routes, considering best, average and bad practices.

3. Results

The materials and energy flows for each of the production steps were used to accomplish the corresponding exergy accounting for each product unit. Exergies are calculated according to the methodology presented in Section 2. As depicted in Fig. 2, the exergy inputs were disaggregated into two parts, energy and materials, whereas the exergy outputs were accounted for products (including the main product and byproducts), wastes (air emissions, water effluents and solid wastes), and the exergy losses, and the efficiencies are given. Final figures for specific systems — steelwork plants or the production route — were obtained by using the main product matrices for 1 t of liquid steel.

3.1. Production routes

Tables 5 and 6 show exergy losses for the production routes analysed. It is important to observe that the overall results, with respect to the total exergy losses and exergy efficiencies, depend on the parameters chosen for each production route.

The semi-integrated route with EAF steelmaking presents the lowest exergy losses among the four routes examined. Power production and EAFs are responsible for the largest part of the exergy losses. Figures for total exergy losses for conventional and new integrated (COREX–BOF) routes are comparable, depending mainly on the exergy efficiencies of the blast furnace and the COREX smelt reduction plant, as well as on material charges in the steelmaking production step. Despite the main cost and environmental advantages of the new integrated routes based on smelt reduction, the exergy losses of a COREX plant are high due to the large use of coal. The export gas is used to produce steam and electricity in a combined-cycle power plant with an efficiency of 48%. Part of the electricity produced is used at other production units in the steelworks. The

Table 1
Main mass and energy flows for the conventional integrated route

	Production steps (consumption)													
	Limestone (t)	Lime (t)	Iron ore (t)	Oil (t)	NG (m^3)	Electricity[a] (kWh)	O_2 (m^3)	Pellet (t)	Sinter (t)	Coal (t)	Coke (t)	Scrap (t)	BF (t)	BOF (t)
Limestone (t/unit)	0	1.6	0	0	0	0.000057	0	0.03	0.15	0	0	0	0.15	0
Lime (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.055
Iron ore (t/unit)	0	0	0	0	0	0	0	1.025	0.95	0	0	0	0.15	0.021
Fuel oil (t/unit)	0.051	0.016	0.003	0	0	0	0	0.003	0	0.008	0	0	0	0
NG (m^3/unit)	0	68	0	0	0	0.0252	0	0	0	0	0	0	30	5
Electricity (kWh/unit)	15	20	27	0	0	0	0.5	40	31	10	30	0	85	26
Oxygen (N m^3/unit)	0	0	0	0	0	0	0	0	0	0	0	0	35	52
Pellets (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0.39	0
Sinter (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	1.16	0
Coal (t/unit)	0	0.07	0	0	0	0.00026	0	0.01	0	0	1.25	0	0.084	0
Coke (t/unit)	0	0	0	0	0	0	0	0	0.052	0	0	0	0.358	0
Scrap (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0124
Pig iron (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0	0.976
BOF steel (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[a] Values for electricity at upstream production processes only. Electricity and steam are generated at steelworks using process gases (36% exergy-efficient). The electricity self-production at steelworks is assumed as 50%. Electricity from the grid is a mix of coal, NG, hydro and nuclear power plants, which gives a grid overall energy efficiency of 40%.

Table 2
Main mass and energy flows for the semi-integrated route

	Production steps (consumption)											
	Limestone (t)	Lime (t)	Iron ore (t)	Oil (t)	NG (m^3)	Electricity[a] (kWh)	O_2 (m^3)	Pellet (t)	DRI (t)	Coal (t)	Scrap (t)	EAF (t)
Limestone (t/unit)	0	1.600	0	0	0	0.000057	0	0.030	0	0	0	0
Lime (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0.067
Iron ore (t/unit)	0	0	0	0	0	0	0	1.025	0	0	0	0
Fuel oil (t/unit)	0.051	0.007	0.003	0	0	0	0	0.003	0	0.008	0	0
NG (m^3/unit)	0	68	0	0	0	0.0252	0	0	300	0	0	10
Electricity (kWh/unit)	15	20	27	0	0	0	0.5	40	105	10	0	500
Oxygen (N m^3/unit)	0	0	0	0	0	0	0	0	0	0	0	30
Pellets (t/unit)	0	0	0	0	0	0	0	0	1.418	0	0	0
DRI (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0.196
Coal (t/unit)	0	0.025	0	0	0	0.00026	0	0.010	0	0	0	0.015
Scrap (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0.874
EAF steel (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0

[a] Values for electricity consumed at the steelworks and upstream production processes. Electricity 100% supplied by the grid. Mix of coal, NG, hydro and nuclear power plants, which gives an overall energy efficiency of 40%.

Table 3
Main mass and energy flows for the new integrated route (COREX–BOF)

	Production steps (consumption)											
	Limestone (t)	Lime (t)	Iron ore (t)	Oil (t)	NG (m^3)	Electricity[a] (kWh)	O_2 (m^3)	Pellet (t)	Coal (t)	Scrap (t)	COREX (t)	BOF (t)
Limestone (t/unit)	0	1.600	0	0	0	0.000057	0	0.03	0	0	0.325	0
Lime (t/unit)	0	0	0	0	0	0	0	0	0	0	0.01	0.055
Iron ore (t/unit)	0	0	0	0	0	0	0	1.025	0	0	0.444	0.021
Fuel oil (t/unit)	0.051	0.016	0.003	0	0	0	0	0.003	0.008	0	0	0
NG (m^3/unit)	0	68	0	0	0	0.0252	0	0	0	0	0	5
Electricity (kWh/unit)	15	20	27	0	0	0	0.5	40	10	0	75	20
Oxygen (N m^3/unit)	0	0	0	0	0	0	0	0	0	0	560	50
Pellets (t/unit)	0	0	0	0	0	0	0	0	0	0	0.932	0
Coal (t/unit)	0	0.070	0	0	0	0.00026	0	0.010	0	0	0.990	0
Scrap (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0.380
Hot metal (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0.720
BOF steel (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0

[a] Values for electricity consumed at upstream production processes only by a mix of coal, NG, hydro and nuclear power plants, which gives an overall energy efficiency of 40%. Electricity and steam are generated in steelworks (100% self-production) using the COREX export gas in a combined-cycle power plant (48% efficient).

Table 4
Main mass and energy flows for the new integrated route (COREX–EAF)

	Production steps (consumption)												
	Limestone (t)	Lime (t)	Iron ore (t)	Oil (t)	NG (m^3)	Electricity[a] (kWh)	O_2 (m^3)	Pellet (t)	Coal (t)	DRI (t)	Scrap (t)	COREX (t)	EAF (t)
Limestone (t/unit)	0	1.6	0	0	0	0.000057	0	0.03	0	0	0	0.325	0
Lime (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0.01	0.067
Iron ore (t/unit)	0	0	0	0	0	0	0	1.025	0	0	0	0.444	0
Fuel oil (t/unit)	0.051	0.007	0.003	0	0	0	0	0.003	0.008	0	0	0	0
NG (m^3/unit)	0	68	0	0	0	0.0252	0	0	0	300	0	0	10
Electricity (kWh/unit)	15	20	27	0	0	0	0.5	40	10	105	0	75	300
Oxygen (N m^3/unit)	0	0	0	0	0	0	0	0	0	0	0	560	40
Pellets (t/unit)	0	0	0	0	0	0	0	0	0	1.418	0	0.932	0
Coal (t/unit)	0	0	0	0	0	0.00026	0	0.01	0	0	0	0.99	0
DRI (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0.350
Scrap (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0.165
Hot metal (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0.583
EAF steel (t/unit)	0	0	0	0	0	0	0	0	0	0	0	0	0

[a] Values for electricity consumed at upstream production processes only by a mix of coal, NG, hydro and nuclear power plants, which gives an overall energy efficiency of 40%. Electricity and steam are generated in steelworks (100% self-production) using the COREX export gas in a combined-cycle power plant (48% efficient).

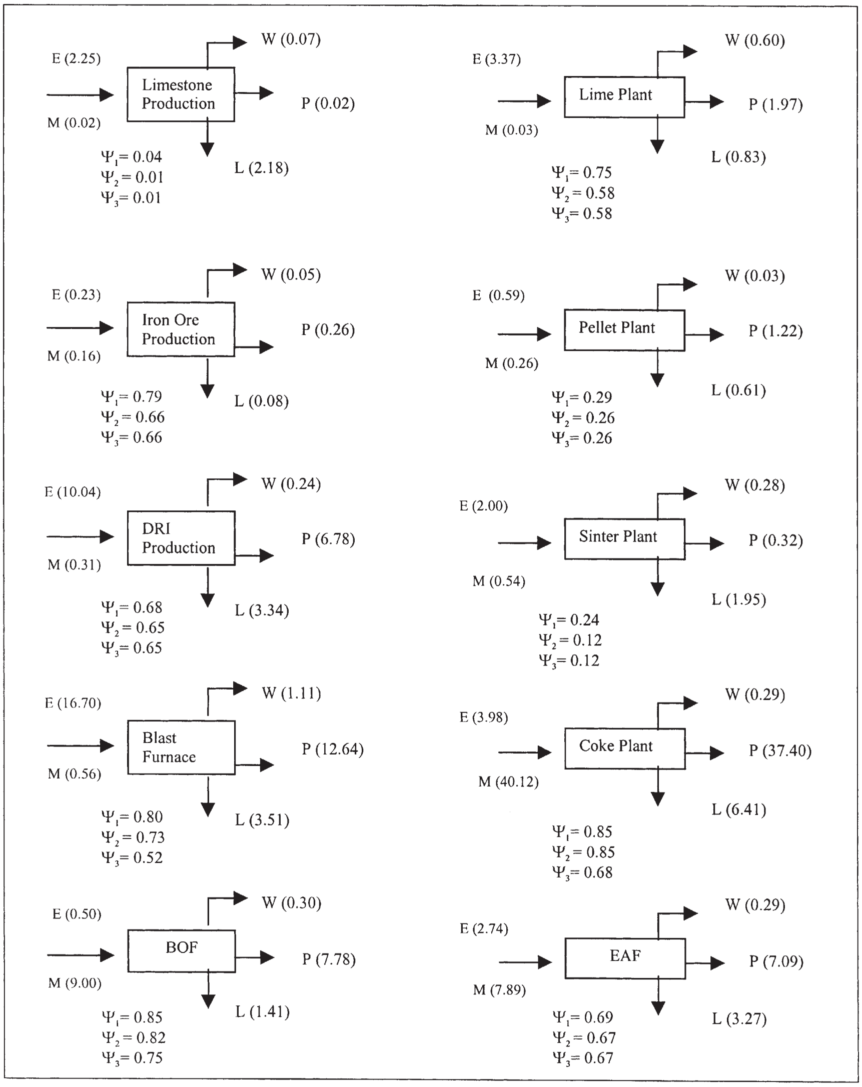

Fig. 2. Exergy accounting for selected production steps (GJ/product unit). E — energy; M — materials; W — wastes (air emissions, water effluents and solid wastes); P — products and byproducts; L — losses.

export gas is available not only for electrical power generation but also for DRI production, for synthesis gas generation in chemical plants, and heating in iron and steel plants [16]. Thus, the export gas credit is accounted for as a thermal byproduct for any other application. Exergy losses are even higher for the COREX–EAF route than for the COREX–BOF route. EAF exergy losses are higher than the BOF losses, and as the electricity consumption in the EAF route is higher, so too are exergy losses for electricity production.

The defined exergy efficiencies are shown in Table 7. These parameters and their variations are discussed in the next section. As expected, semi-integrated steelworks are the most efficient in exergetic terms, Ψ_2=67%, while for the new integrated steelworks COREX–BOF Ψ_2=50%,

Table 5
Exergy losses for conventional integrated and semi-integrated steel production routes by production step

	Product unit	Exergy loss (MJ/product unit)	Conventional integrated (BOF)		Semi-integrated (EAF)	
			Product input (unit/t liquid steel)	Exergy loss (GJ/t liquid steel)	Product input (unit/t liquid steel)	Exergy loss (GJ/t liquid steel)
Limestone product	tonne	2179	0.447	0.97	0.151	0.33
Lime plant	tonne	830	0.065	0.05	0.067	0.06
Iron ore	tonne	83	1.633	0.14	0.285	0.02
Fuel oil[a]	tonne	0	0.035	0	0.011	0
Natural gas	m^3	3	46	0.15	89	0.28
Power plant	kWh	5	274	1.36	620	3.08
Oxygen plant	m^3	2	86	0.20	30	0.07
Pellet plant	tonne	612	0.381	0.23	0.278	0.17
Sinter plant	tonne	1946	1.132	2.20	0.000	0
Coal	tonne	199	0.676	0.13	0.181	0.04
Coke plant	tonne	6410	0.412	2.64	0.000	0
Scrap[b]	tonne	0	0.124	0	0.874	0
DRI	tonne	3338	0	0	0.196	0.65
Blast furnace	tonne	3512	0.976	3.43	0	0
BOF	tonne	1414	1	1.41	0	0
EAF	tonne	3265	0	0	1	3.26
Total exergy losses				12.92		7.97

[a] Exergy losses from fuel oil production in oil refineries are not considered in our analysis.
[b] Exergy losses from scrap transportation are not considered in our analysis.

and for the conventional integrated steelworks Ψ_2=48%. Compared with the other steelworks, the new integrated COREX–EAF is the least exergy-efficient, with Ψ_2=43%. The differences between Ψ_2 and Ψ_3 indicate the relative exergy importance of byproducts for a particular kind of steelworks. In the case of considering only the main products, the exergy efficiencies are lower for the conventional and new integrated routes, which show how gaseous, solid and liquid byproducts actually enhance the overall exergy efficiency of the processes. The differences between the exergy losses from steelworks only and the complete production routes[5] demonstrate the influence of upstream production steps in total exergy losses for steel production.

3.2. Sensitivity analysis

Process parameters were modified in order to assess the sensitivity of the results presented in Tables 5–7 for variations in process parameters. Some ranges of exergy losses and exergy efficiencies were obtained by changing selected factors, as shown in Figs. 3–5. Relative figures

[5] The production steps considered are those included in Tables 1–4. The important contribution of materials transportation as well as other steps, like machine manufacturing and other inputs, is not considered.

Table 6
Exergy losses for new integrated (COREX–BOF and COREX–EAF) steel production routes by production step

	Product unit	Exergy loss (MJ/product unit)	New integrated (COREX-BOF)		New integrated (COREX-EAF)	
			Product input (unit/t liquid steel)	Exergy loss (GJ/t liquid steel)	Product input (unit/t liquid steel)	Exergy loss (GJ/t liquid steel)
Limestone product	tonne	2179	0.375	0.82	0.374	0.82
Lime plant	tonne	830	0.062	0.05	0.073	0.06
Iron ore	tonne	83	1.028	0.09	1.327	0.11
Fuel oil[a]	tonne	0	0.032	0	0.033	0
Natural gas	m^3	3	19	0.06	137	0.44
Power plant	kWh	3.9	370	1.44	656	2.56
Oxygen plant	m^3	2	453	1.03	366	0.84
Pellet plant	tonne	612	0.671	0.41	1.042	0.64
Coal	tonne	199	0.820	0.16	0.758	0.15
Scrap[b]	tonne	0	0.38	0	0.165	0
DRI	tonne	3338	0	0	0.352	1.17
COREX hot metal	tonne	12273	0.720	8.84	0.583	7.16
BOF	tonne	1884	1	1.88	0	0
EAF	tonne	2645	0	0	1	2.64
Total exergy losses				14.78		16.58

[a] Exergy losses from fuel oil production in oil refineries are not considered in our analysis.
[b] Exergy losses from scrap transportation are not considered in our analysis.

Table 7
Exergy efficiencies and exergy losses from distinct steelworks[a]

		Conventional integrated[b]	Semi-integrated[c]	New integrated COREX–BOF[d]	New integrated COREX–EAF[e]
Steelworks only	Exergy efficiency Ψ_1	0.56	0.69	0.55	0.49
	Exergy efficiency Ψ_2	0.48	0.67	0.50	0.43
	Exergy efficiency Ψ_3	0.30	0.67	0.25	0.28
	Exergy losses (GJ/t liquid steel)	10.9	3.3	13.0	12.8
Steel production route	Exergy losses (GJ/t liquuid steel)	12.9	8.0	14.8	16.6

[a] The results may vary with the energy and material consumption of each process.
[b] Steelworks include lime plant, power plant, oxygen plant, sinter plant, coke plant, blast furnace and basic oxygen furnace.
[c] Steelworks include electric arc furnace.
[d] Steelworks include lime plant, power plant, oxygen plant, COREX plant and basic oxygen furnace.
[e] Steelworks include lime plant, power plant, oxygen plant, COREX plant and electric arc furnace.

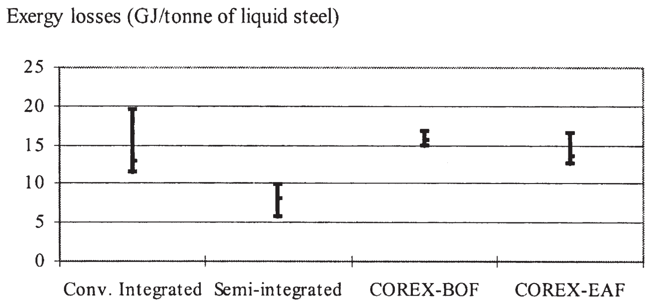

Fig. 3. Ranges of exergy losses for the production routes (GJ/t liquid steel).

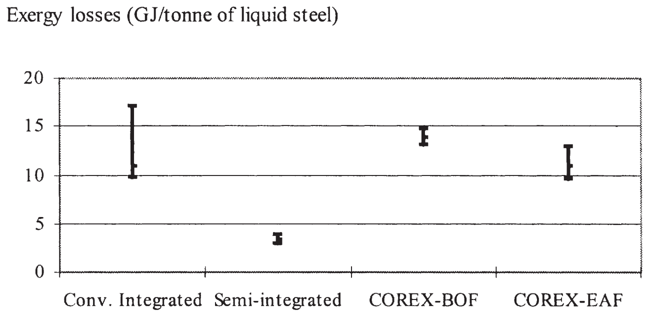

Fig. 4. Ranges of exergy losses for the steelworks only (GJ/t liquid steel).

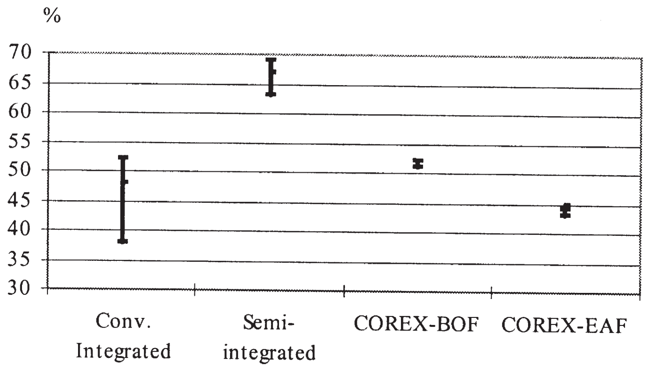

Fig. 5. Ranges of exergy efficiencies Ψ_2 for the steelworks only (%).

for comparisons are more important than absolute ones since some production steps, such as casting, rolling, finishing and product transportation, are not taken into account. For the conventional integrated and semi-integrated routes, we modified the process parameters in order to model less energy-efficient plants with higher pollution discharges. For the new integrated plants, the main changes are not related to COREX plants, as we consider the same values for coal consumption and COREX gas use. The main variables are the EAF or BOF charges of scrap, DRI and hot metal, which influence electricity and oxygen consumption and exergy losses per tonne of liquid steel produced.

The chemical composition variations for the major inputs, products and wastes represent a small fraction of the exergy losses, with the exception of lower energy contents used for coal. As the coal consumption and exergy values are high, small differences in the latter can result in large differences in the total results. Different exergy values were adopted for different types of coal (e.g., coking coal, steam coal for electricity generation, non-coking coal for COREX and other production steps).[6]

3.2.1. Conventional integrated route

Conventional integrated plants with less efficient sinter plants, coke plants, blast furnaces and basic oxygen furnaces present exergy losses that can be as high as 17 GJ per tonne of liquid steel. The wide range of exergy losses reflects the wide set of process designs and efficiencies of this production route. The most efficient plants present exergy losses comparable with steel plants using smelt reduction processes, as depicted in Figs. 3 and 4. The range could be wider if old and very inefficient plants were considered.

3.2.2. Semi-integrated route

Semi-integrated plants with high electricity consumption and using electricity from inefficient coal-fired power plants can increase the exergy losses of the complete production route to around 10 GJ per tonne of liquid steel. Thus, the efficiency of the electricity generation plant heavily affects the final figure for the semi-integrated route. For the steelworks only, the electricity consumption is the main factor, but for the complete route the different charges of scrap and DRI are also important. Variations in the exergy losses and efficiencies for the steelworks are smaller than for the other processes, even with large differences in electricity consumption and material charges.

3.2.3. New integrated route with smelting reduction

We have assumed that the hot metal produced is consumed only at the steelworks. The material charge flexibilities for the COREX–BOF plants (typically 75% hot metal and 25% scrap) are lower than for COREX–EAF plants (maximum 75% hot metal). Using different charges of scrap, DRI and hot metal for the latter results in a wider range of exergy losses. As the exergy losses in the COREX step are high, lower hot metal charges in EAF result in lower exergy losses per tonne of liquid steel, even considering the lower electricity consumption in EAF. Smelt reduction is a relatively new process and the plants are operated with a high use of the COREX gas. If the parameters of the COREX process were modified (e.g., coal consumption and COREX gas use), the ranges would be wider.

3.3. Other studies

Some authors have also provided exergy analyses of steel production. Selected characteristics and results of the selected studies are shown in Table 8. Although the studies use the same

[6] The amount and composition of COREX export gas depend on the composition of the coal. A wide variety of coals can be used with the COREX process.

Table 8
Overall description of exergy studies dealing with steel production systems

	Masini and Ayres [8]	Beer et al. [7]	Michaelis et al. [10]	This study
Scope	US steel industry (1988)	IISI reference plant (1996)	UK steel industry (1994)	Plants within ranges
Processes	Mix of BOF (53%), EAF (33%), casting (9%) and OHF (5%)	BOF route	Mix of BOF route (75%) and EAF route (25%)	BOF route, EAF route and COREX routes with BOF and EAF
System boundaries	LCI including steel plants (ingot) and mining (iron ore)	Integrated steel plant (finished product) and power plant	LCI including steel plants (finished product), mining (iron ore and coal), material transport, oxygen plant and power plant	LCI including steel plants (liquid steel), mining (iron ore, coal and limestone), oxygen plant and power plant
Energy disaggregation	Resources, products, losses, emissions (air and water) and solid wastes	Resources, products and losses (external and internal)	Resources, products, exergy consumption and wastes (general)	Resources, products, losses, emissions (air and water) and solid wastes
Energy losses	12.4 GJ/t steel ingot	11.6 GJ/t hot-rolled steel	19.0 GJ/t finished steel	See Table 7 and Figs. 3–5

methodology, they differ in scope. Hence comparing the studies is not straightforward. Even so, we note some similar results, such as the exergy losses for the same system boundaries.

Masini and Ayres [8] pointed out the excellence of the exergy method as a tool for resource and waste accounting. Comparing exergy losses with our results is made difficult because the results are not disaggregated by process. Beer et al. [7] calculated exergy losses per tonne of rolled steel from an IISI reference plant. If the exergy losses associated with casting and rolling steps are excluded, the result falls at the bottom of the range of exergy losses of integrated plants depicted in Fig. 4, which indicates an efficient plant. The study by Michaelis et al. [10] comprised a more complete exergy LCI applied to the UK iron and steel industry. Exergy losses are higher mainly due to the inclusion of rolling and finishing production steps and materials transportation. Using input–output analysis, Lenzen and Dey [22] calculated an energy content of 40 GJ/t steel for the Australian steel industry, which includes capital, imports and higher-order requirements from supplying industries. According to these authors, typical system boundaries used in conventional LCI based on process analysis cover only about 65% of the total energy requirements of steel.

4. Discussion

4.1. Exergy of pollutants

Exergy accounting has shown that total emissions and wastes represent a relatively minor part of the output exergy of steel production systems (Fig. 2 and Table 9). Although exergy values

Table 9
Exergy values for outputs and losses from distinct steelworks

Exergy	Conventional integrated		Semi-integrated		New integrated COREX–BOF		New integrated COREX–EAF	
	GJ/t liquid steel	%	GJ/t liquid steel	%	GJ/t liquid steel	%	GJ/t liquid steel	%
Liquid steel[a]	7.1	34.4	7.1	67.0	7.1	24.0	7.1	28.3
Byproducts[b]	0.8	3.7	0	0	7.9	26.7	3.7	14.7
Air and water emissions	0.9	4.5	0.04	0.4	0.4	1.4	0.4	1.6
Solid wastes[c]	0.9	4.5	0.2	1.9	1.2	4.1	1.1	4.4
Exergy losses	10.9	52.9	3.3	29.7	13.0	43.8	12.8	51.0
Total[d]	20.6	100	10.6	100	29.6	100	25.1	100

[a] Chemical exergy only.
[b] Part of COREX export gas not used to produce electricity and steam for on-site use constitute the COREX byproducts.
[c] Total solid wastes including recycled on-site, recycled off-site and landfilled.
[d] Total inputs=total outputs+losses.

of pollutants cannot adequately measure the ecotoxicity of waste streams,[7] in more aggregated levels it can show the importance (from an efficiency point of view) of preventing pollution or even collecting and controlling it for recycling (e.g., dusts and sludges). Instead of particular exergy values for each pollutant, total volume released is the main factor for total figures, as can be noted from Tables A1 and A2, in which the exergy values for air emissions, water effluents and solid wastes for the conventional integrated route are calculated.

4.2. Exergy losses and efficiencies

Exergy accounting of energy and materials flows is highly dependent on the parameters used to describe the industrial systems. Nevertheless, comparing specific steelmaking processes and specific production routes altogether can reveal the main characteristics of each system. In the case of steel, exergy losses are helpful to indicate improvement opportunities not only in the steelworks but also for upstream production processes, as well as to provide directions for efficiency gains.

Comparisons of exergy losses and efficiencies between some particular production steps and the production route can reveal organizational characteristics of the industrial system. It is interesting to observe the low exergy efficiencies of pellet and sinter plants. The ore preparation provided by these production steps constitutes an important factor to the relatively high operational and exergy efficiency of blast furnaces. The exergy accounting for coke plant byproducts and for solid wastes from blast furnaces and basic oxygen furnaces is presented in Tables A2 and A3.

[7] The total exergy of solid wastes from semi-integrated plants is lower than from other processes, as shown in Table 9. Nevertheless, EAF dust and sludges are hazardous wastes containing large amounts of zinc and lead, which create some problems for recycling.

Exergy values for outputs (steel, byproducts, emissions and solid wastes) are shown in Table 9. While the main exergy values are associated with steel and losses for conventional integrated and semi-integrated steelworks, byproducts from steelworks with smelt reduction present high values as well. As explained in Section 3, part of the COREX export gas is used to produce steam and electricity and the credit is accounted for as a byproduct.

Currently, steelmaking technology is developing towards more compact and flexible steelworks. New energy-efficient technologies for steelmaking include smelt reduction, near-net-shape casting, steelmaking at lower temperatures, waste heat recovery at high temperatures and improved scrap melting processes [7]. In this paper we have calculated the exergy flows for steelmaking routes with a COREX plant, currently the only commercial smelt reduction process. Considering potential future improvements, we can verify the high exergy losses associated with the high temperatures typically used in these processes. Smelt reduction processes eliminate the need for coke production, as well as (in the future) the need for ore agglomeration,[8] resulting in cost and environmental advantages, but demand higher coal and oxygen inputs. An exergy analysis of technological and organizational evolution and trends in steel production systems could address these trade-offs.

5. Conclusions

5.1. Steel plants

Even with inefficient EAF steelmaking, exergy losses are the lowest for the semi-integrated plants. Depending on the energy efficiency of particular plants, conventional integrated steelworks can present lower exergy losses than the new integrated steelworks with COREX. Even so, the exergy efficiencies Ψ_1 and Ψ_2 for COREX–BOF plants are higher than those of energy-efficient sinter–coke–BF–BOF plants. Overall exergy losses for steel plants with smelting reduction depend heavily on the hot metal charge in the steelmaking step. On the other hand, Ψ_2 efficiencies present narrow ranges due to the variations of the export gas production per tonne of steel according to the hot metal use. At COREX–EAF plants, it is surprising to note their low Ψ_2 efficiency once high export gas recovery rates are assumed. Other exergy analyses are recommended for comparing possible arrangements in steel plants with smelting reduction units. For all types of steel plant, energy-saving measures are the most important alternatives to reduce exergy losses. Even so, use of byproducts in other economic sectors, decreasing air and water emissions and, finally, recycling of solid wastes remain as fundamental tasks to improve the overall efficiency and reduce environmental impacts from a wider perspective.

5.2. Steel production routes

For integrated routes, although exergy losses per tonne of steel at upstream production steps are lower than at steelworks, these losses are significant and could be reduced: first, by increasing

[8] Exergy losses for ore agglomeration (sintering, pelletization) may not be needed in future smelt reduction processes such as Cyclone Converter Furnace (CCF).

Table A1
Exergy accounting of selected air emissions and water effluents for a conventional integrated steelworks with particular emission factors

	Exergy (kJ/g pollutant)	Emissions[c] (g/t liquid steel)	Total exergy (MJ/t liquid steel)
Air emissions			
Dust[a]	7.878	932	7
SO_2	4.892	1502	7
NO_x	1.209	1057	1
CO	9.821	25×10^3	243
CO_2	0.451	1430×10^3	645
VOCs	42.239	278	12
H_2S	23.826	101	2
HCl	2.318	79	0.2
HF	3.999	26	0.1
PAHs[b]	41.000	0.7	0.03
PCDD/F[b]	13.000	11×10^{-6}	15×10^{-8}
Benzene	42.292	8	0.3
NH_3	19.841	0	0.6
CH_4	51.842	15	0.8
Total exergy in air emissions			920
Water effluents			
TSS[a]	7.878	80	0.6
Ammonia	19.841	10	0.2
Chlorides	1.341	1000	1.3
Fluorides	2.829	10	0.03
Cyanides	32.478	2	0.1
Sulfides	23.999	5	0.1
Phenol	33.242	1.2	0.04
Oil and grease	37.450	50	1.9
Sulfates	1.139	1000	1.1
Total exergy in water effluents			5.3

[a] Exergy of dust and TSS (total suspended solids) were calculated using the mass and exergy values of dusts and TSS for each production step.
[b] The exergy values of PAHs (polycyclic aromatic hydrocarbons) and PCDD/F (polychlorinated dibenzo-*p*-dioxins and furans) were estimated based on the main constituent compounds.
[c] The total emissions were calculated based on average emission factors [15,20] by production step and on the processes parameters presented in Table 1.

exergy efficiencies at upstream steps; and second, by decreasing the need for mining products or externally provided energy carriers, such as off-site electricity. For semi-integrated routes, in which the electricity is not produced within the EAF plants, the overall exergy losses are highly dependent on the efficiency of electricity generation. For smelting reduction routes, high exergy losses associated with high coal use in the COREX unit are balanced by some advantages in terms of cost, environmental burdens and operational flexibility. For all types of steel production route, it is important to confront exergy losses and efficiencies with other energy, economic and environmental factors.

Table A2
Exergy accounting for byproducts from a coke plant

Byproducts	Energy (kJ/kg byproduct)	Byproducts[a] (kg/t coke)	Byproducts[b] (kg/t liquid steel)	Total exergy (MJ/t liquid steel)
Tar	35,000	40	16.32	571
Light oil (BTX)	35,000	15	6.12	214
Naphthalene	41,000	0.03	0.01224	1
Sulfuric acid	1666	7	2.856	5
Ammonium sulfate	4999	3	1.224	6
Total exergy in byproducts from coke plants				797

[a] Emission factors for well-designed and operated COG cleaning plants. Other values may apply and are dependent on site parameters.
[b] Using 0.408 t coke/t liquid steel as a conversion factor.

5.3. *Exergy accounting*

We can confirm some of the most cited limits of exergy analysis when applied to industrial systems in an aggregated level. Exergy accounting may not provide an answer for the analysis of all aspects of material flows (e.g., ecotoxicity of pollutants and wastes). However, the exergy concept provides additional information in more aggregated levels by measuring resources and wastes on a common basis. In particular, LCI exergy analysis can address some trade-offs (for energy and materials flows) arising from diverse technological options for steelworks and the complete production route.

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Appendix A

As an example, Table A1 presents exergy accounts of air emissions and water effluents for the conventional integrated route. The emission factors in mass come from average values [15,20] by production step and from the processes parameters presented in Table 1. The emission factors can vary depending on pollution control and pollution prevention technologies, and on material inputs and energy consumption, which would result in different exergy values. Nevertheless, the

Table A3
Exergy accounting for solid wastes from blast furnaces and basic oxygen furnaces

Solid waste (SW)	Exergy[a] (kJ/kg SW)	SW[b] (kg/t product)	SW[c] (kg/t liquid steel)	Exergy (MJ/t liquid steel)	Landfilled[d] (%)	Recycled on-site[d] (%)	Recycled off-site[d] (%)	Ex. landfilled (MJ/t liquid steel)	Ex. recycled on-site (MJ/t liquid steel)	Ex. recycled off-site (MJ/t liquid steel)
BF slag	1612	300	293	472	2%	0%	98%	9	0	463
BOF slag	1479	132	132	195	26%	37%	37%	51	72	72
BF dust	11,546	12	12	135	33%	65%	2%	45	88	3
BOF dust	2139	4	4	9	12%	55%	33%	1	5	3
BF sludge[e]	7505	5	5	37	33%	65%	2%	12	24	1
BOF sludge[e]	1390	17	17	24	42%	51%	7%	10	12	2
Total exergy in solid wastes				871				128	201	543

[a] The exergy values for slags, dusts and sludges were calculated using composition data presented in [15,20] for each solid waste considered. Variations are discussed in Section 3.2, Sensitivity analysis.
[b] Typical specific production factors were obtained from [15,20].
[c] Using 0.963 t pig iron/t liquid steel as conversion factor.
[d] Percentages for solid wastes landfilling, on-site and off-site recycling were obtained from [15].
[e] Considering sludges with 35% water content.

important issue here is to compare the aggregated exergy figures for air emissions and water effluents with other exergy flows, namely exergy inputs, products and losses. The final figures using lower emission factors can be three times as low as the air emission factors presented, but represent small changes to the overall results and comparison.

It is worthwhile to observe the particular exergy values by weight for each pollutant and how the emission values per tonne of liquid steel constitute the main factor with respect to total exergy values of pollutants per tonne of liquid steel (Table 10). Even pollutants with high exergy values by weight, such as benzene, polycyclic aromatic hydrocarbons (PAHs), methane and volatile organic compounds (VOCs), present low total exergy values due to their low emission values. On the other hand, CO_2 and CO present higher total exergy values per tonne of liquid steel due to the higher emission factors involved.

The exergy accounting for coke plant byproducts and for solid wastes from blast furnaces and basic oxygen furnaces is presented in Tables A2 and A3.

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